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Progress in development of multiple-quantum-well retromodulators for free-space data links

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Abstract. We present an update on the progress of the development of the Naval Research Laboratory's (NRL's) multiple-quantum-well retromodulators for compact, low-power communications. We report results for data-in-flight on a small, unmanned aerial vehicle at up to 5 Mbps, in preparation for real-time video transfer using an array of devices. This data was taken at Chesapeake Bay Detachment. We also report transference of color video using wavelet compression at 15 and 30 frames/s, at 4 to 6 Mbps in the lab, at eye-safe intensity levels. The unit is a corner cube modulator using a 980-nm shutter. A five-element array was used for the data-in-flight. First results of our 1550-nm devices are also presented as progress in a "cat's eye retromodulator." [DOI: 10.1117/1.1572155]

Subject terms: multiple-quantum-well retromodulators; modulating retroreflectors; retromodulators; cat's eye retromodulator; free-space optical communications.

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1 Introduction

Due to its promise of wide bandwidth, freedom from frequency allocations issues, comparatively small communications terminals, and low power requirements, free-space optical communications has emerged in recent years as an attractive alternative to the conventional radio frequency (rf) approach. There are many applications, where reducing the parasitic payload requirements for the onboard communications system would be advantageous and the Naval Research Laboratory (NRL) has been developing multiple-quantum-well (MQW) retroreflectors for just this purpose.[1,2]

In this paper, we report progress in the implementation of the wide aperture MQW modulating retroreflector (MRR) for video and multiple mega-bit-per-second (Mbps) data transfer for compact, lightweight, low-power optical data transfer.

The device couples an electroabsorptive narrow-band tunable shutter with a standard optical corner cube. It is lightweight (of the order of ounces), low power (milliwatts), compact (centimeter-level diameters), and radiation resistant.[3] When coupled with a sensor and drive electronics, the package can serve as the communications payload for a remotely located platform.

The payload is interrogated by a laser and modulated by the shutter. The modulated retroreflected light is received and demodulated at the transmit/receive location. This technique is especially suited to asymmetric links where the communications payload located remotely can be quite small—the size of a quarter for a single device and the size of a fist for an array. This asymmetry is enabled by the range-to-the-fourth loss inherent in the use of retroreflected links. That is, the received power in the far field is proportional to

$$\frac{P_{\text{laser}} D_{\text{retro}}^4 D_{\text{rec}}^2 T_{\text{cl}}^2 T_{\text{atm}}^2}{\theta_{\text{div}}^2 R^4}, \qquad (1)$$

where P_{laser} is the transmit power, D_{retro} is the diameter of the retroreflector, D_{rec} is the receiver diameter, T_{atm} is the transmission coefficient of the atmosphere, T_{cl} is the transmission coefficient of clouds, θ_{div} is the divergence of the transmit beam, and R is the range. The onus of the link

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14. ABSTRACT
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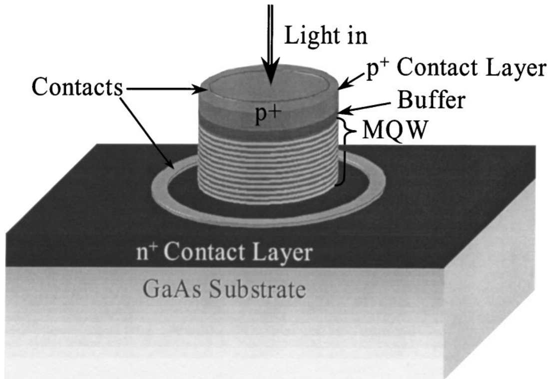

Fig. 1 Schematic of the MQW modulator geometry showing layer structure and electrical contacts for a surface normal optically transmissive device.[3]

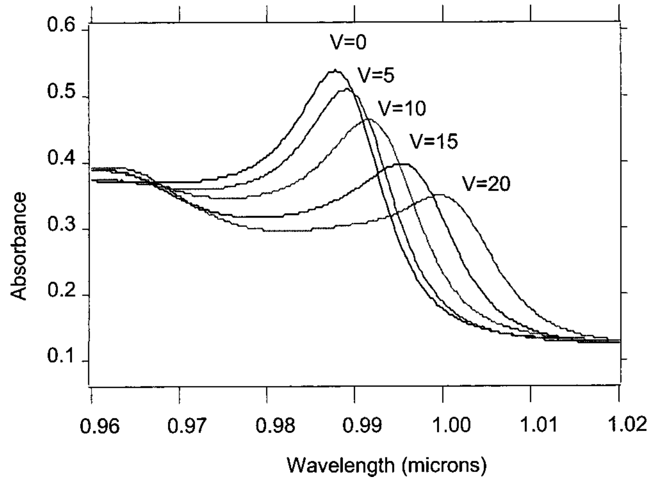

Fig. 2 Switching characteristic of an InGaAs-based MQW modulator.

consequently falls on the power of the transmitter, the size of the receive telescope, and the quality of the detector and receiver. Although the range-to-the-fourth component clearly dominates loss of signal in air, off-the-shelf components can support multi-kilometer-scale links.

In previous work,[4] we reported data-in-flight on a micro-UAV (unmanned aerial vehicle) of 400 and 910 kbps at ranges of the order of 35 m. In this effort, psuedorandom codes varying from 300 kbps through 5 Mbps drove an array of five devices. Data was obtained with nominal bit error rates over ranges of 30 to 100 m in daylight.

After the field test, real-time color video was transmitted over a 30-m link in the laboratory using wavelet compression and a single corner cube retroreflector. Video was transmitted in an eyesafe regime at 1 Mbps at 15 frames/s (fps) and at up to 6 Mbps at 30 fps at higher incident power levels, though still eye-safe in light levels.

2 MQW MRR

MRR devices utilizing MQW technology have a number of advantages. In addition to drawing milliwatts to support megabits per second, low mass, and compactness, they are inherently faster than alternatives. MQW retromodulators can support up to 12 Mbps with centimeter-level diameters and higher with millimeter-level diameters.[5] The devices are essentially narrow-band tunable optical filters and so they enable secure data transfer over carrier frequencies not susceptible to the band allocation problems characteristic of radio frequency links.

The devices are essentially *p-i-n* devices made from InGaAs/AlGaAs using molecular beam epitaxy (MBE). When a moderate voltage (in the range of 12 to 20 V) is placed across the device in reverse bias, the absorption feature changes, both shifting in wavelength and changing in magnitude. Thus, the transmission of the device near this absorption feature changes dramatically and can serve as a solid state on-off shutter. A schematic of the modulator architecture and switching capability is shown in Figs. 1 and 2 for an InGaAs-based MQW modulator.

As shown in Fig. 2, the device demonstrates how the contrast ratio changes as a function of drive voltage for the 980-nm device used in these experiments and how the device can be used as a tunable filter over a narrow range of wavelengths.

3 Field Test

Field tests were conducted at the NRL Chesapeake Bay Detachment facility in Chesapeake Beach, Maryland. A micro-UAV, a helicopter approximately 1.5 m in length, was fitted with a payload consisting of an array of retromodulators, a digitizing unit, impedance-matching driver circuitry, and requisite battery power packs.

3.1 *Payload Configuration*

Five 0.63-cm-diam InGaAs/AlGaAs modulators were used in this series of tests. The modulators were designed for transmissive operation. All were fabricated from the same wafer with a center frequency of 980 nm and bandwidth of approximately 10 nm. None were segmented. They were mounted in front of corner cube retroreflectors, which were antireflection coated at 980 nm and had a protected silver coating on the reflecting surfaces.

The mounted devices each presented a 30-deg FWHM field of view and measured 2 cm in diameter. These devices were selected to perform within 5% of each other in terms of reflectance, contrast ratio, and switching speeds. The five units were situated in an elliptical array to compensate for reduced control of the model helicopter's motion in yaw. The array was configured to present a 60-deg field of view to the interrogating laser. Each mounted retromodulator weighed 0.4 oz and the configured array on an aluminum mount weighed about 14 oz. A photo of the array is shown in Fig. 3.

The modulators were driven in parallel with 12 to 15 V to provide contrast ratios of about 2.5:1 on all five units. A sequence of pseudorandom codes were set in 2-s patterns of increasing bit rates from 300 kbps to 5 Mbps, with code lengths of 63 chips.

The array required less than 400 mW, or ~75 mW per retromodulator, and the microprocessor required 10 to 20 W, depending on the data rate. No effort in this demonstration was made to minimize the power draw for the microprocessor.

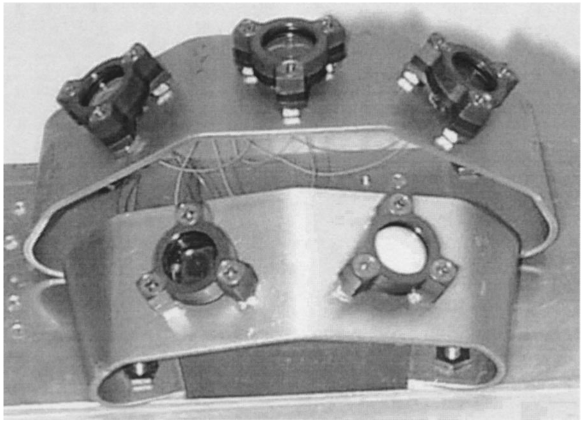

Fig. 3 Retromodulator array for UAV data-in-flight; MRR units have a 980-nm center frequency; devices populate the array with a 30-deg separation with retros about 5 cm apart, which present a 60-deg field of view.

3.2 *Transmit/Receive*

The helicopter was illuminated with an optical transmit/receive (Tx/Rx) design that employed an annular mirror for shared aperture transmit and receive. A 980-nm laser diode was fiber coupled to zoom optics, which enabled changes in outgoing beam divergence from 2 through 13 mrad. Received retroreflected light was directed to the tracking and detection optics and electronics by the mirror. A narrow-band dichroic mirror split 90% of the 980-nm line to an avalanche photodiode (APD). The remaining white light and 10% of the 980-nm lights was directed to a small video camera which was used for in-line target acquisition and tracking. A block diagram of the system is shown in Fig. 4.

A scintillometer recorded the structure constant C_n^2 over the horizontal path simultaneously with the data acquired in flight. A portable weather station recorded relative humidity, barometric pressure, and temperature over the data taking periods as well.

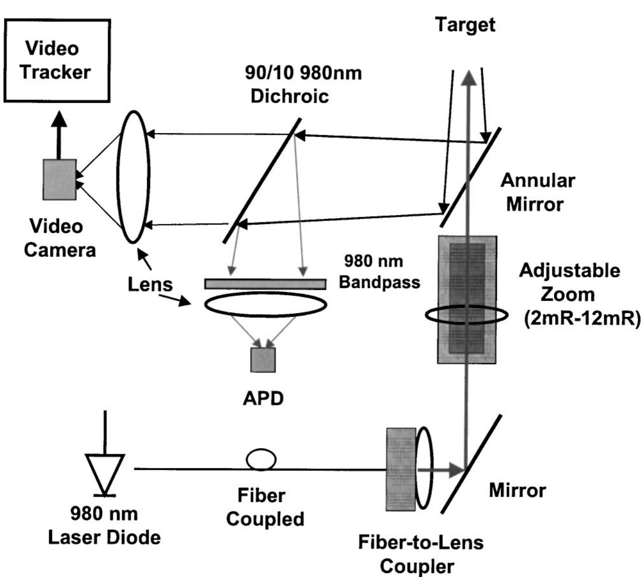

Fig. 4 Block diagram of Tx/Rx system for UAV data-in-flight; aperture sharing is accomplished with an annular mirror; zoom optics enable *in situ* changes in divergence; in-line acquisition and tracking is enabled by chromatic aperture sharing.

3.3 *Acquisition and Tracking*

The pointing, acquisition, and tracking were accomplished with the in-line video signal, a tracking unit, and an intensity-centering algorithm. The 10% passthrough of 980-nm light enabled self-tracking using the retroreflected light from the array. This method is an improvement over the first demonstration in that LEDs were not used to aid in acquisition and tracking. However, it was found that the in-line video tracking using the images of the helicopter was easier in full daylight, even with a narrow-band filter in front of the acquisition camera.

Using the techniques described, the beam was kept on target continuously and ranged varied from about 30 to 100 m for the tests. Elevation angles were about 30 to 45 deg. This method is ultimately more efficient in terms of payload power requirements compared to the tracking technique using an array of LEDs. The approach also offers a larger field of view for interrogation.

3.4 *Results*

Results for different data rates are shown in Fig. 5. From this figure, we can see that the pulse trains are discernible up to 5 Mbps. An electronic filter was put on the input of the digital recorder to filter out additional noise from the band, but it is expected that the array could support greater than 5 Mbps with some degradation in bit error rate. Ranges for this data were of the order of 30 to 100 m. It is expected that the devices, which were shown to support up to 10 Mbps in the laboratory, could support greater bandwidth for the field tests, if required.

The contrast ratio of the retromodulators was of the order of 2:1 when driven at 12 V. The returns remained robust over the ranges and propagation occurred under relatively strong turbulence conditions in midday. We did not explore the complete parameter set in this demonstration but operated in the regime to support essentially nominal bit error rates (BERs) over the link. The noise on the signal was due primarily to atmospheric effects, which was very evident at the longer ranges. For the lower data rates (750 kHz and 1.25 and 2.5 MHz) the effective SNR was so high that measuring a BER was impractical. For the 5-MHz case, we were operating in the transition band of our receiver due to the filter.

Figure 6 shows the power spectrum of modulated and unmodulated light captured in flight. A 30-mW output into a 12.5-mrad beam presented an average incident flux on target of about 7 nW/cm^2 at 30 m and about 150 pW/cm^2 at the longer ranges. Although the impact of the strong range dependence on the signal strength was evident in a reduction of average SNR at the longer ranges, the effect of atmosphere was clearly more pronounced, evidenced by larger noise fluctuations.

The structure constant for the horizontal path varied but was of the order of $C_n^2 = 4 \times 10^{-13}$ with a high variance for most of the data acquisition period. This structure-constant profile is a signature of high turbulence where closed-form solutions based on Kolmogorov theory breaks down. Traces

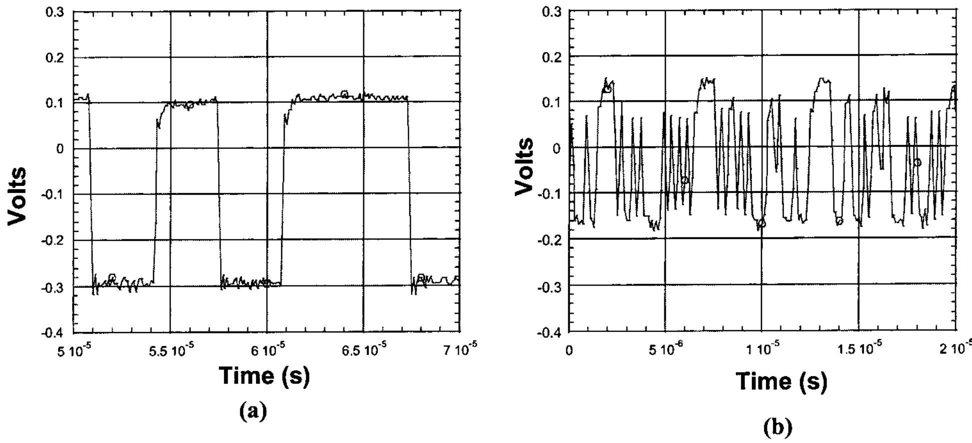

Fig. 5 Traces of data-in-flight at ranges from about 30 to 50 m. Data streams varied continuously through (a) 300 kbps and (b) 5 Mbps. Data was obtained without bit drop out in daylight outside at ranges up to 100 m.

of the structure constant as a function of time are shown in Fig. 7.

4 Color Video

4.1 *Experiment*

In this experiment, a Sony camcorder was connected to an L3 wavelet compression unit using a standard NTSC interface. The output was then sent through an impedance-matching circuit to drive one of the 980-nm retromodulators. This ''payload'' was then placed approximately 30 m from the laser transmitter/receiver interrogator in a laboratory environment. The incident light from the 980-nm source was varied from 5 to 8 mW/cm^2, where transfer at completely eye-safe light levels defined the bound. Frame and bit rates were varied to explore image quality. The L3 wavelet compression unit enables error corrective coding. We chose the Reed-Solomon block-encoding option for transmission.

A photograph of the communications terminal is shown in Fig. 8. The form factor for the compression unit is small—of the order of $8\times3\times10$ cm. The mounted retromodulator measures about 2.5 cm on a side for a single unit. The modulator itself required 80 to 130 mW to drive the link. The compression unit required 9 W, which dominated the power draw requirement.

4.2 *Results*

At the lower flux levels, a 1-Mbps link was supported and color video was transferred at 15 fps. At the higher flux levels, 30 fps were supported at 4 to 6 Mbps without significant bit drop-out. Figure 9 shows still images of the transmission at 4 mbps at 30 fps inside the laboratory environment. A video clip is available on the project's web site.[6]

Based on qualitative analysis from the transmission, images at 15 fps are certainly informative enough to enable the observer to obtain useful information. When the beam was blocked, transmission stopped, freezing the frame. Frame recovery was of the order of milliseconds.

A key aspect in this demonstration was that the very low power required by the retromodulator unit itself exposed the power requirement of the digitizing component in the communications terminal. This points to a new area for technology investment.

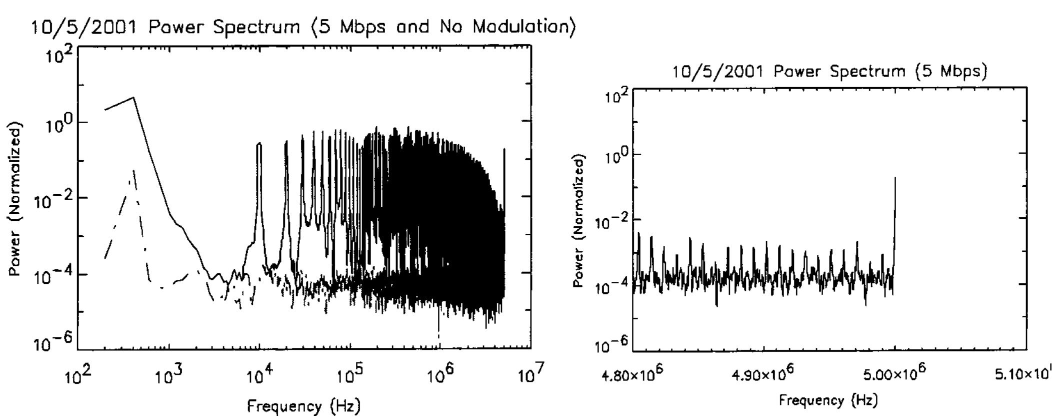

Fig. 6 Power spectrum of the modulated and unmodulated returned light. The inset is a detail showing that 5 Mbps was received with the system. An electronic filter was placed on the output of the detector to suppress noise from scattering.

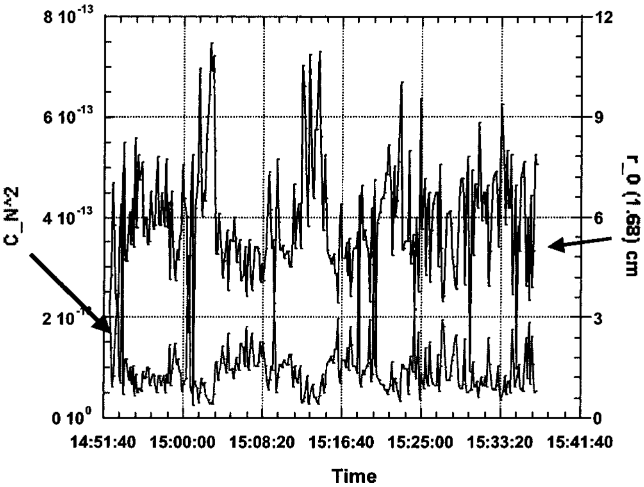

Fig. 7 Traces of the structure constant C_n^2 as a function of time during the data-in-flight measurements. Instantaneous values varied significantly but the average value was of the order of 4×10^{-14}.

5 New Initiatives

5.1 *Eye-Safe Retromodulators*

In addition to the MQW devices designed and fabricated from 850 nm through 1.06 μm, we have begun to design and fabricate devices at 1550 nm. This wavelength is in the ''eye-safe'' regime where substantial investment by the telecommunications industry has advanced the development of supporting components. In addition there is a significant transmission window through the earth's atmosphere at this wavelength.[4]

Lattice strain makes fabrication of effective devices using InGaAs/AlGaAs substrates and MBE very difficult. The new devices are being designed in InGaAs/InAlAs. The new class of material relieves strain but presents a new set of challenges. The greater propensity to form defects from the manufacturing process can ultimately lead to limits in contrast ratios.

First MQW retromodulators were fabricated with 1-mm diameters. When scaled to the 0.63-cm device, we can expect comparable performance to the 980-nm device in terms of modulation rates. Figures 10 and 11 show some performance results of these first devices. In Fig. 10, absorbance plots indicate that contrast ratios of 2.3:1 are possible. Figure 11 shows that modulation rates of at least 20 Mbps are viable. Data rates of 40 Mbps were also supported but are not shown. We will phase these into the field tests as the processing and fabrication matures.

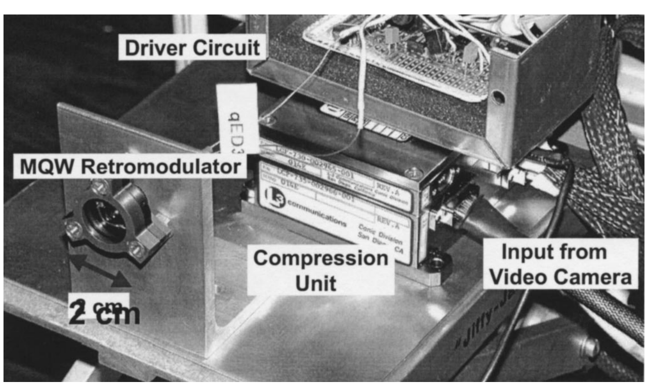

Fig. 8 Photograph of the communications terminal. The unit was comprised of a 980-nm retromodulator coupled to an L3 wavelet compression unit, impedance-matching drive circuitry, and a power supply. The link was obtained with 130 mW on the modulator supporting up to 6 Mbps, 30 fps.

Fig. 9 Still image from the video transmission transferred over the MRR link at 4 Mbps at 30 fps inside the laboratory environment.

5.2 *"Cat's Eye" Retromodulators*

The MQW modulator is essentially a p-i-n device. As such, there is a fundamental trade between speed and power consumption, since both are limited by the resistor-capacitor time constant. That is, the speed is proportional to $1/R_{\mathrm{mod}}D_{\mathrm{mod}}^2$, where R_{mod} is the sheet resistance of the modulator and D_{mod} is the diameter. The power consumed is proportional to $D_{\mathrm{mod}}^2V^2f$, where V is the drive voltage and f is the modulation rate.

The electrical characteristics of the MQW device limit the modulation rate to about 1 to 20 MHz/cm^2 and heating becomes a concern at the higher modulation rates due to the

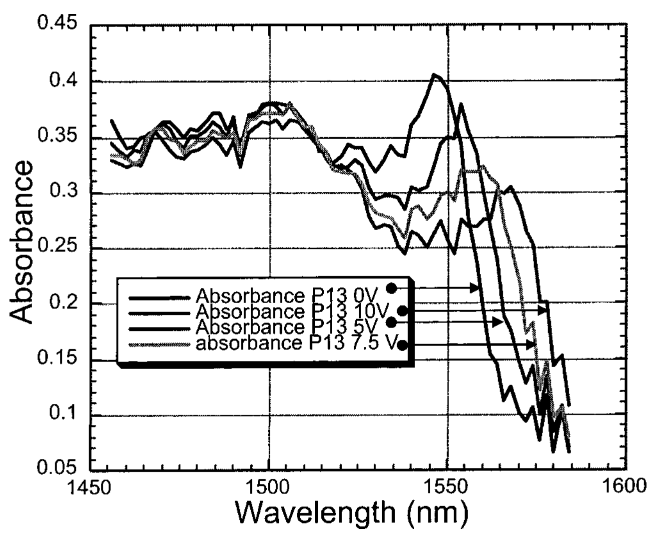

Fig. 10 Absorbance versus wavelength for 1550-nm devices. First efforts are yielding MQW modulators that have 2.3:1 contrast ratios.

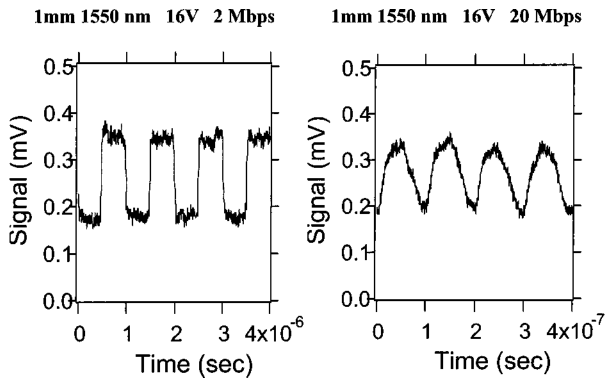

Fig. 11 Modulation traces are shown for the 1550-MQW devices. The 1-mm-diam devices are shown to support at least 20 Mbps.

higher drive power requirements. Consequently, there is a fundamental limit to the speed of the corner cube device. This has motivated the NRL to consider a new class of retromodulators: the ''cat's eye'' retromodulator.[5,7]

In these devices, the ''cat's eye'' retroarchitecture enables us to use a much smaller MQW modulator. Essentially, an array of very small devices—of the order of a millimeter each—can be placed in the pupil or focal plane of a cat's eye retromodulator, illuminating just one or a few ''pixels'' of the modulator array. The MQW device is manufactured to exploit its ability to serve as a detector as well as a modulator. Only the ''pixel'' or ''pixels'' illuminated must be modulated. This approach enables much higher speeds and significantly lower drive powers. The trade is that the optics and supporting electronics are more complex and heavier. However, the element still can be compact and lightweight compared to conventional laser communications terminals.

The first devices were constructed using 1-mm 980-nm devices and a design using off-the-shelf optical components produced a 4-times diffraction-limited device. The devices supported a data rate of 40 Mbps. Figures 12 and 13 are a schematic of the idea and a photograph of the first reduction to practice, respectively.

Future work will include the design, fabrication, and testing of a diffraction-limited ''cat's eye.'' We will then combine it with 1550-nm devices, as discussed in the previous section to create fast, eye-safe units that promise to provide more than a magnitude improvement in modulation rate.

6 Conclusions

This work reports progress in the use of the NRL MQW retromodulators. Data-in-flight was recovered with essentially no bit errors for up to 5 Mbps in the field using a five-element array of devices. Bandwidth was limited by an electronic filter used to filter out noise, not by the device itself. Ranges were of the order of 30 to 100 m. Wavelet-compressed color video was transmitted using the device from 15 fps at 1 Mbps through 30 fps at 6 Mbps over 30 m in the laboratory.

In future efforts, we will mount the camera, compression unit, and impedance circuits with the array onto a micro-UAV to obtain real-time video-in-flight. The work indicates that pointing can hold the beam on the array for requisite dwell times and the compressed video can be transferred effectively, as shown in the laboratory. We will also explore parameter space for viable video links over longer ranges and lower intensities.

Device development at 1550 nm will continue as will the investigation of effective architectures to increase device speeds to better than 100 Mbps.

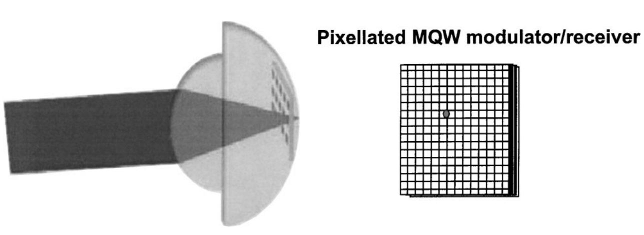

Fig. 12 Concept of a focal plane ''cat's eye'' retromodulator.

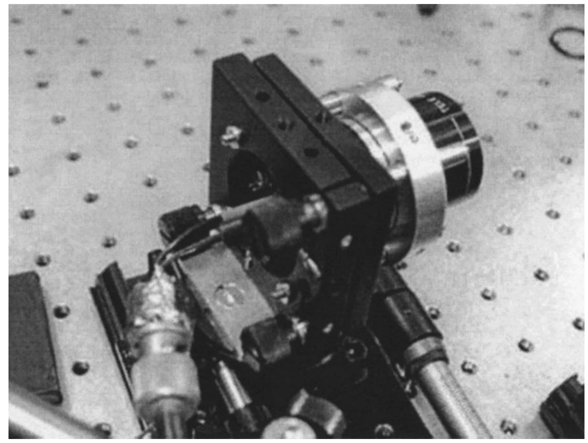

Fig. 13 Photo of a first ''cat's eye'' retromodulator. This device supports of the order of 40 Mbps and is about 10 times the diffraction limit.

Acknowledgments

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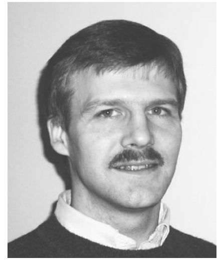

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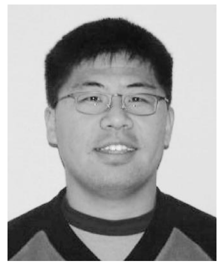

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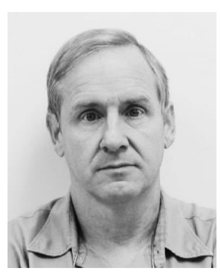

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